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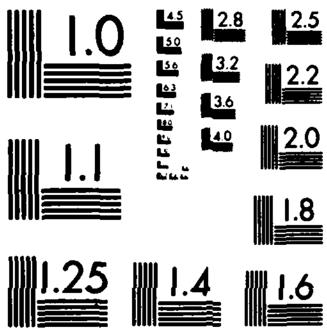

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Technical Report E-194
May 1984

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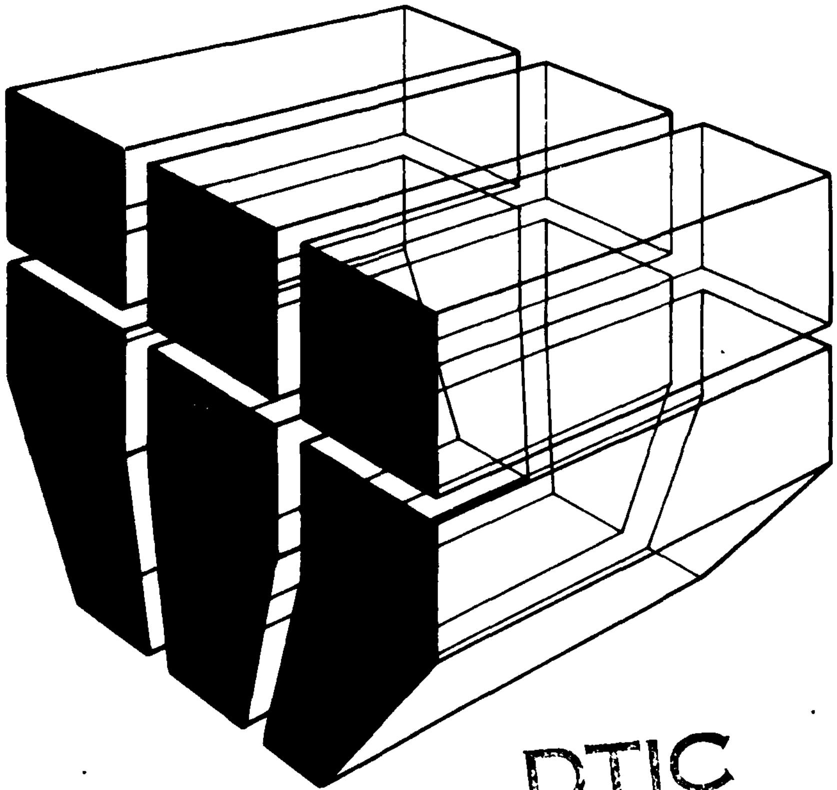
DEVELOPMENT OF A MODULAR SOLAR DOMESTIC HOT WATER SYSTEM FOR DEPARTMENT OF DEFENSE BARRACKS

by
D. M. Joncich
R. E. Kirts



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This report describes the development of a modular concept for solar domestic water heating on Department of Defense (DOD) barracks buildings. In this approach, the solar energy system consists of only two major components: a collector module and a heat-exchanger-pump-storage tank (HPS) module.

The collector module is comprised of a three-collector assembly on an aluminum rack for ground or roof mounting, designed for the interconnection of several modules. The

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HPS module contains the system pump, heat exchanger, thermal storage vessel, expansion tank, controls, Btu meter, and other minor components.

A survey of existing DOD barracks indicated that only three discrete sizes of HPS modules would be required to service approximately 75 percent of the entire barracks inventory nationwide. The appropriate size for a given application is selected by a simple, manual procedure which requires a minimum of user input. The features of the installed system include provisions for system filling/draining, freeze protection, and flow balancing.

A prototype modular system was placed into operation in March 1983 on an 80-person barracks at the Naval Construction Battalion Center in Port Hueneme, CA. This system, consisting of approximately 900 sq ft of collectors and a 1200-gal tank, is operating properly with a thermal performance near its design goal. Although the system is not economically feasible in current market conditions, its cost effectiveness will improve as fuel prices rise.

FOREWORD

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The Energy Systems Division, U.S. Army Construction Engineering Research Laboratory (CERL) and the Mechanical and Electrical Engineering Department, Naval Civil Engineering Laboratory (NCEL) were the performing organizations. Mr. R. E. Kirts is with NCEL at Port Hueneme, California. Mr. R. G. Donaghy is Chief of the Energy Systems Division, and Dr. Charles K. Smith is head of the Mechanical and Electrical Engineering Department.

COL Paul J. Theuer is Commander and Director of CERL, and CAPT Norman D. Falk is Commanding Officer of NCEL. Dr. L. R. Shaffer and Dr. Donald L. Birkimer are the Technical Directors at CERL and NCEL, respectively.

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DEVELOPMENT OF A MODULAR SOLAR DOMESTIC HOT WATER SYSTEM FOR DEPARTMENT OF DEFENSE BARRACKS

1 INTRODUCTION

Background

The Army is considering solar domestic water heating as part of an effort to reduce baseline Fiscal Year (FY) 1975 total facilities energy consumption 20 percent by FY 1985.* The technology exists for constructing these systems in Department of Defense (DOD) buildings. The primary constraint to widespread implementation of these systems is one of economics as many DOD solar feasibility studies have demonstrated.[1] One of the major factors leading to the unfavorable economics for these projects is the high cost of the custom system design and installation required for each project. In addition, many contractors place high contingency factors in the bids because they lack experience with designing and installing solar heating systems. Although DOD does not normally supply solar equipment to its contractors, it was believed that the economic viability of solar heating systems might be improved if a system of standard, government-furnished, pre-assembled components (or modules) was developed that would be applicable to a large number of installations. Modularization potentially could (1) reduce system design and installation costs and (2) eliminate common design errors. Here, the installation contractor would be responsible only for installing government-furnished modules and not for system sizing or performance.

The concept of constructing solar heating systems from a few standardized components offers a feasible method of matching the requirement for increased energy conservation to DOD building inventory characteristics. DOD has many installations, so the cumulative savings from reduced solar design and installation costs would be substantial. Also, a carefully designed modular system could be installed either on new construction or as a retrofit. Finally, using standard designs for several applications may permit introduction of simplified procurement procedures for the solar system modules, such as large-scale purchases and stocking in the Federal supply system.

Objective

The objective of this effort was to design, construct, and test a modular solar domestic water heating system that could be installed cost-effectively at a large number of DOD barracks nationwide.

Approach

The information in this report was developed as follows:

1. Determination of domestic water heating loads within DOD barracks.

2. Analysis of concepts for solar domestic water heating systems.

3. Specification and procurement of modular solar components.

4. Installation of a modular solar domestic water heating system.

5. Test and evaluation of the modular solar concept and the system hardware.

Scope

The modular solar heating system described in this report was designed primarily to supply domestic hot water (DHW) to military barracks. Because most solar feasibility studies indicate domestic water heating is much closer to being cost-effective than space heating, this effort emphasizes domestic water heating. Military barracks were selected as the type of buildings most suited to initial application of the modular solar heating system concept because so many are constructed to standard designs.

2 DEVELOPMENT OF THE MODULAR CONCEPT

Selection of System Configuration and Components

In developing a modular concept for solar domestic water heating in military barracks, a number of candidate solar system configurations were surveyed. The advantages and disadvantages of each approach were analyzed, and a final DOD configuration was selected.

**Army Facilities Energy Plan* (Department of the Army, Office of the Chief of Engineers, 4 November 1982), p 8.

[1] U.S. Department of Defense, *DOD Solar Energy Project Summaries* (Office of the Chief of Engineers, DAEN-MPE-E, March 1980).

Table 1
Solar System Features

Features	System Types: Single Tank Direct	Single Tank Indirect	Double Tank Direct	Double Tank Indirect	Air	Thermo-siphon
Thermal performance	+	0	0	0		0
Applicability to new/retrofit			+	+		
Method of freeze protection		+		+	0	
Ease of installation		0		0	0	
Installed cost	+	0	+	0	0	+
Reliability		+		+	0	+
Operating cost		0		0	0	+

\+ Better than average.
0 Average.
– Worse than average.

Following nomenclature developed by the National Bureau of Standards, the systems considered are described by the following terms: direct, indirect, one-tank, two-tank, air, and thermosiphon.[2] Figure 1 shows six possible combinations of these system descriptors.

In direct systems, domestic water is preheated in the collectors directly. These systems contain no heat exchanger. When no solar energy is available for collection, freeze protection in this approach is provided either by: (1) draining the collectors or (2) recirculating warm water from the storage tank through the collector array as necessary.

For the indirect systems, the potable water is isolated from the fluid in the collector loop by a heat exchanger. Here, freeze protection is typically achieved with a nonfreezing heat transfer fluid (such as a glycol, silicone oil, or hydrocarbon-based liquid) in the collector loop. Alternatively, water may be circulated through the collectors, provided it is drained during cold, sunless periods.

Direct and indirect systems may contain either one or two thermal storage tanks. When one tank is used, the system is designed to assure that the water in the storage vessel stratifies to such an extent that solar energy can preheat the water in the bottom of the tank while the auxiliary source of energy heats the top. For the two-tank system, the solar-preheated domestic water is contained in a vessel separate from the conventional water heating tank.

In the air system, sunlight heats air in the collectors, and the collected solar energy is transferred to the domestic water with a duct-mounted coil in the collector loop. Using air as the heat transfer fluid eliminates the concern for collector fluid freezing.

The thermosiphon system uses potable water in the collector loop. The system operation is based on the fact that cold, high-density water flows down from the storage tank, forcing warm, low-density water back to the tank to replace it. The system contains no pumps or heat exchangers, but it must be drained before the onset of freezing conditions.

The relative advantages and disadvantages of each system pictured in Figure 1 were analyzed for applicability to this project.[3] The results of this analysis are summarized in Table 1. Here, the six systems were ranked on a three-point scale (+, 0, –) in each of the

[2] S. Liu and A. Fanney, "Comparison of Experimental and Computer-Predicted Performance for Six Solar Domestic Hot Water Systems," *American Society Heating Refrigerating Air-Conditioning Engineers Transactions*, Vol. 86, Part 1 (1980), p 823.

[3] See for example, U.S. Department of the Army, *Final Reliability and Materials Design Guidelines for Solar Domestic Hot-Water Systems*, ANL/SDP-11, SOLAR/0909-81/70 (September 1981).

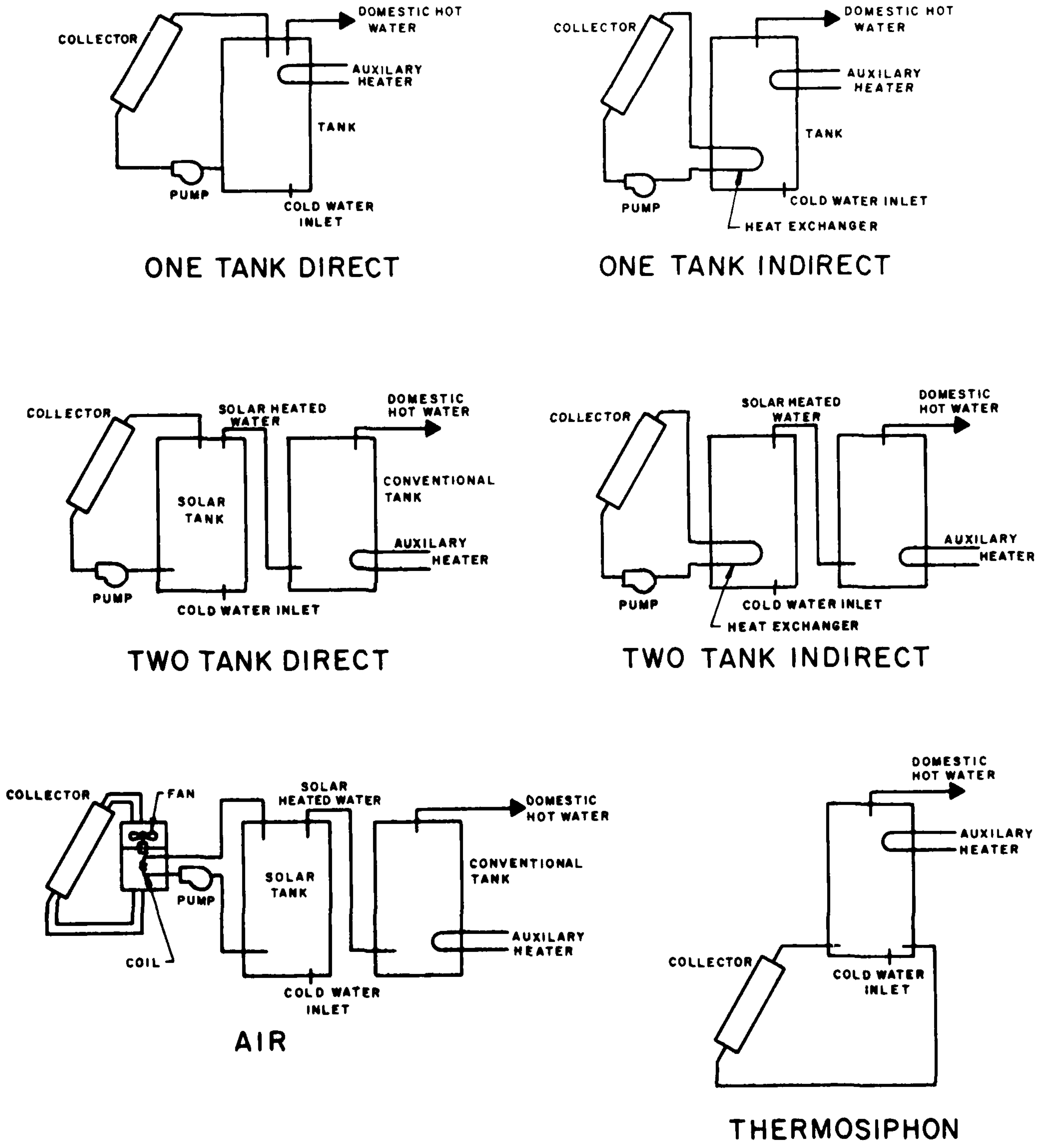

Figure 1. Summary of candidate system types.

Table 2
Summary of Flat Plate Collector Characteristics

Feature	Selection	Rationale
Number of glazings	Single	Minimize collector array weight
Type of glazing material	Glass	Good spectral response, durable
Plate composition	Varies	Allow Cu, Fe, Al, with Cu passageways
Plate surface selectivity	None	Dictated by cost vs performance
Collector manifold arrangement	Internal headers	Minimize external array piping
Type of insulation	None	Determined by cost vs performance
Composition of collector enclosure	Aluminum	Requires no painting, reduces maintenance costs

seven categories shown. For example, in considering thermal performance alone, the one-tank direct system ranked better than average (+), the air system worse than average (−), and the remaining systems neutral (0). These factors considered, the two-tank indirect system was selected as the basis for developing the DOD modular concept.

Once the system configuration had been established, the existing inventory of commercially available hardware was surveyed.[4] In particular, several options were considered for the type of collector, heat exchanger, and heat transfer fluid to be incorporated into the system final design.

The three most common types of collectors in production at this point in the project development were flat-plate, evacuated tube, and concentrating/tracking units. Because sizing of the other system components depends on the type of collector used, only one of the three could be selected as the basis for the modular system. In general, evacuated tubes and tracking collectors were developed for improved performance in high-temperature applications. Given that high temperatures are not required for domestic water heating, it was felt that the increased efficiency of these collectors would not offset their higher initial cost. Problems with control mechanisms in the tracking units had also been noted in previous solar demonstrations. Finally, neither the evacuated tube nor tracking models are as readily available as the flat-plate units. For these reasons, neither high-performance collector was considered further.

Table 2 summarizes the characteristics of available flat-plate collectors and describes the features considered important for this application. A brief rationale for each decision is also provided. For example, only singly glazed collectors were allowed, to minimize the weight of the installed collector array.

In summary, any singly glazed (with glass), internally manifolded, flat-plate collector with copper passageways and an aluminum enclosure was considered acceptable for the modular solar project.

The question of heat exchanger selection was strongly related to the choice of the heat transfer fluid.[5] Heat exchangers that provide single isolation between the source of heat and potable water are more readily available and less expensive than units with double isolation. These facts considered, a single isolation exchanger was incorporated into the system design. In this case, a nontoxic fluid must be used in the system collector loop to satisfy building codes; inhibited propylene glycol was selected over silicone oil because of the glycol's reduced cost and superior heat transfer characteristics. To reduce the number of system components, the heat exchanger was specified as the type installed directly in the thermal storage vessel. This design is in contrast to having the exchanger totally external to the tank. An in-tank exchanger needs only a single system pump as opposed to the two pumps required with an external heat exchanger.

Major components for the modular system are shown in Figure 2. The system consists of two primary parts: several collector modules and the heat exchanger-pump-storage (HPS) module.

Operation of the system pictured in Figure 2 is relatively straightforward. The collectors absorb a fraction of the solar energy incident upon them, thereby raising their temperature. When the collector

[4]*Solar Products Specifications Guide* (Solar Vision Inc., Harrisville, NH, updated periodically).

[5]G. Franta et al., *Solar Design Workbook*, Report SERI/SP-62-308 (Solar Energy Research Institute, 1981).

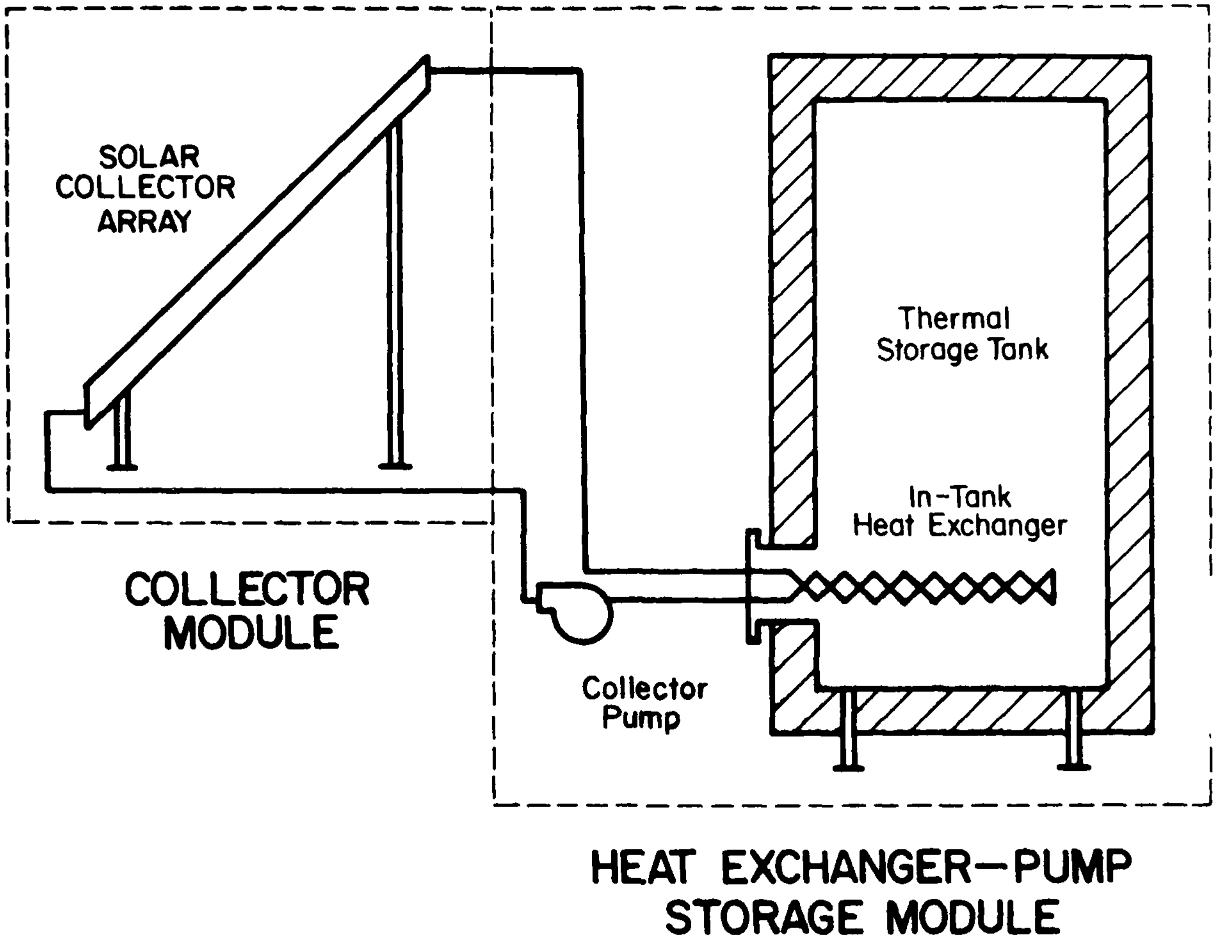

Figure 2. Modular system schematic (major components only).

temperature is sufficiently higher than the tank temperature, the system pump is activated. Thermal energy contained in the collector loop is transferred to storage via the system heat exchanger. The tank is heated to an extent determined by (1) the magnitude of solar radiation available to the collectors and (2) the quantity of cold water drawn through the tank. The details of component sizing are addressed later in this chapter.

Variables Affecting System Performance

For a given area of collector modules, the fraction of the total thermal load supplied by the system pictured in Figure 2 for domestic water heating is determined primarily by two factors: the onsite availability of solar radiation and the quantity of energy required for domestic water heating. The magnitudes of both these quantities were examined for a range of climates and barracks to allow the sizing of the modular components.

Figure 3 provides a perspective of the mean daily insolation levels for the United States.[6] This figure shows that the solar radiation ranges from less than 1150 Btu/sq ft/day in the North to over 1980 Btu/sq ft/day in the Southwest. A realistic modular system design must be flexible enough to account for these variable insolation levels.

The quantity of thermal energy, Q_L, required annually for the heating of domestic water is given by Eq 1:

$$Q_L = \rho V C_p \Delta T \qquad \text{[Eq 1]}$$

[6] From D. Christensen, *Solar Energy for Buildings Handbook*, DOE Report ORO-5362-T1 (October 1979).

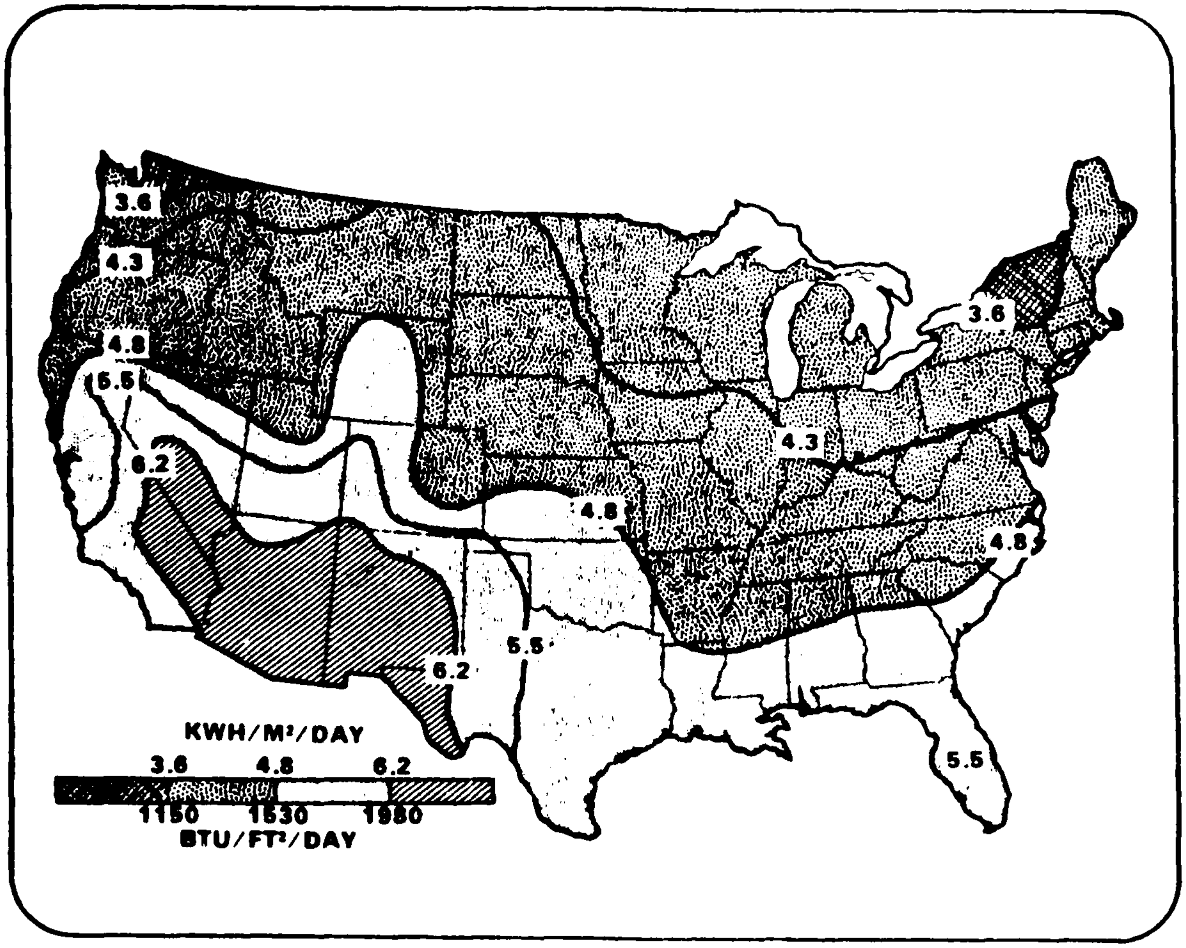

Figure 3. Annual average of daily insolation levels. (Adapted from D. Christensen, p 71.)

where ρ is the density of water, V is the volume of water to be heated in a year, C_p the specific heat of water, and ΔT the temperature increase desired. For this analysis, ρ and C_p are assumed to be constant. In military installations, domestic water is normally heated from 55° to 110°F; this implies a temperature rise of 55°F.

The quantity of water to be heated each year is determined by the occupancy of the barrack under consideration and the daily per capita consumption of domestic hot water. An Army Technical Manual recommends conventional domestic water heating equipment be sized for 30 gal/person/day.[7]

The results of a study by the Naval Civil Engineering Laboratory (NCEL) indicated that, for Navy Bachelor Enlisted Quarters (BEQ), hot water usage ranged from 30 to 40 gal/person/day.[8] To substantiate these findings, water meters were installed in a three-story BEQ at the Naval Construction Battalion Center in Port Hueneme, California. Results of the meter readings for a 4-month period are summarized in Table 3. Although the consumption of hot water fluctuated, the 30-gal/person/day figure is seen as reasonable.

To calculate the total annual energy requirement for domestic water heating, the number of occupants per

[7]Technical Manual (TM) 5-810-5, *Plumbing* (Department of the Army, 1 November 1982).

[8]J. King, *Study of Domestic Hot Water Use in Navy Bachelor Enlisted Quarters*, Technical Note N-1387 (NCEL, April 1975).

Table 3
BEQ Domestic Hot Water Consumption

Date (1979)	Average Daily Usage (gal/day)	Personnel on Board	Per Capita Consumption (gal/person/day)
1 May - 7 May	3328	64	52
8 May - 14 May	2187	70	31
15 May - 21 May	2418	78	31
22 May - 28 May	2193	74	30
29 May - 3 June	1870	74	25
4 Jun - 10 Jun	2259	73	31
11 Jun - 17 Jun	2063	68	30
18 Jun - 26 Jun	2130	65	33
27 Jun - 2 Jul	2130	64	33
3 Jul - 11 Jul	1379	63	22
12 Jul - 16 Jul	2450	55	45
17 Jul - 24 Jul	2083	68	31
25 Jul - 6 Aug	2229	55	41
7 Aug - 21 Aug	1923	57	34

building must also be known. An analysis of a study by the U.S. Army Facilities Engineering Support Agency indicated that 75 percent of the existing DOD inventory consisted of barracks containing 50 to 400 persons.[9] (Only permanent structures with flat roofs were included in this tabulation.) The modular approach at this point was limited to buildings with this occupancy range.

Refinement of the Modular Approach

The first step in refining the design for the modular system consisted of estimating roughly how much collector area would be required per person to deliver a reasonable amount of solar energy for domestic water heating. To accomplish this, a "reference" system was defined, and several F-Chart simulations were carried out for representative climates within the continental United States.[10] The results, summarized in Table 4, indicated that a collector area of roughly 10 sq ft/person would provide an annual solar fraction averaging 50 percent.

The assumptions made in generating this information are itemized at the bottom of the table. Here, the reference system is for a 100-person barrack, having a per capita hot water consumption of 30 gal/person/day. The remaining system thermal parameters are essentially F-Chart default values, with the added assumption that a heat exchanger of 0.4 effectiveness isolated the collector fluid from the potable water supply.

The insight gained by requiring 10 sq ft of collector per person allowed the modular design to be completed. For typical values of solar insolation and hot water usage, it was determined that the entire inventory of DOD barracks with an occupancy range of 50 to 400 could be serviced if modular systems were available in three sizes. This finding is summarized in Table 5 for the systems labeled I, II, and III. System I, for example, intended for barracks with 50 to 100 occupants, consists of 24 to 48 collectors (at 20 sq ft each) with a total array area in the range 480 to 960 sq ft. It contains a 1200-gal storage tank, a heat exchanger with a 70-sq ft surface area, and a 1/4 hp pump.

Because the tank volume for this size system is not fixed, the ratio of storage volume to collector array area varies from 1.25 to 2.5 gal/sq ft, depending on the number of collectors involved, rather than being fixed at the F-Chart default of 2 gal/sq ft. In addition, the System I pump was sized with the capacity to deliver 0.5 gpm/collector for the number of collectors shown in Table 5. Similarly, the heat exchanger surface area was adjusted to provide an effectiveness of around 0.4 under typical conditions expected for the system.

[9]G. Stewart and J. Hughes, *Solar Domestic Water Heaters in DOD Buildings*, FESA Report FESA-RT 2004 (September 1975). (For Official Use Only).

[10]W. Beckman, S. Klein, and J. Duffie, *Solar Heating Design by the F-Chart Method* (Wiley-Interscience, 1977).

Table 4
Summary of F-Chart Analysis
(Solar Fraction = 50 percent)

System Location	Average Insolation (Btu/sq ft/day)	Collector Area (sq ft/person)
Madison, WI	1190	15.2
Indianapolis, IN	1270	15.8
Columbia, MO	1400	12.5
Laramie, WY	1510	9.7
Davis, CA	1590	9.5
Fort Worth, TX	1640	10.5
Ely, NV	1730	8.6
Las Vegas, NV	1880	7.1
Phoenix, AZ	1920	7.3

Assumptions:
100-person barrack
30 gal/person/day hot water usage
55°F water temperature rise
Collectors facing south, tilted at latitude angle
No incident angle modifier
.40 heat exchanger effectiveness
2 gal storage/sq ft collector

It must be realized that, with high domestic hot water usage and low solar availability, the largest System I may not have enough collector area to deliver the solar fraction desired. Although the preliminary system sizing was developed using F-Chart, for simplicity it was desired to base the modular concept on an approach not requiring a computer. A manual method of determining the appropriate system size for a specific application is described in the next section.

System Selection

In developing a methodology for solar energy system design, CERL performed several hundred solar system computer simulations for typical Army buildings in various parts of the country. The results indicated that, if expressed in the proper dimensionless terms, the thermal performance of a given system type could be represented by a single performance curve for all buildings at all locations.[11] This result was also published at approximately the same time by researchers at the Los Alamos National Laboratory.[12]

[11] D. C. Hittle, D. Holshouser, and G. Walton, *Interim Feasibility Assessment Method for Solar Heating and Cooling of Army Buildings*, Technical Report E-91/ADA026588 (CERL, 1976); D. M. Joncich, D. J. Leverenz, D. C. Hittle, and G. Walton, *Design of Solar Heating and Cooling Systems*, Technical Report E-139/ADA062719 (CERL, 1978).

[12] J. D. Balcomb, D. P. Grimmer, J. C. Hedstrom, and K. C. Herr, *Pacific Regional Solar Heating Handbook*, Informal Report/LA-6242-MS (Los Alamos Scientific Laboratory, 1976).

Table 5
Summary of Modular Approach

Variable	System I	System II	System III
Number of occupants	50 100	100 200	200 400
Collector array area (sq ft)	480 960	960 1920	1920 3840
Number of collectors	24 48	48 96	96 192
Storage volume (gal)	1200	2400	4800
Pump size (hp)	1/4	1/2	3/4
Heat exchanger area (sq ft)	70	100	200

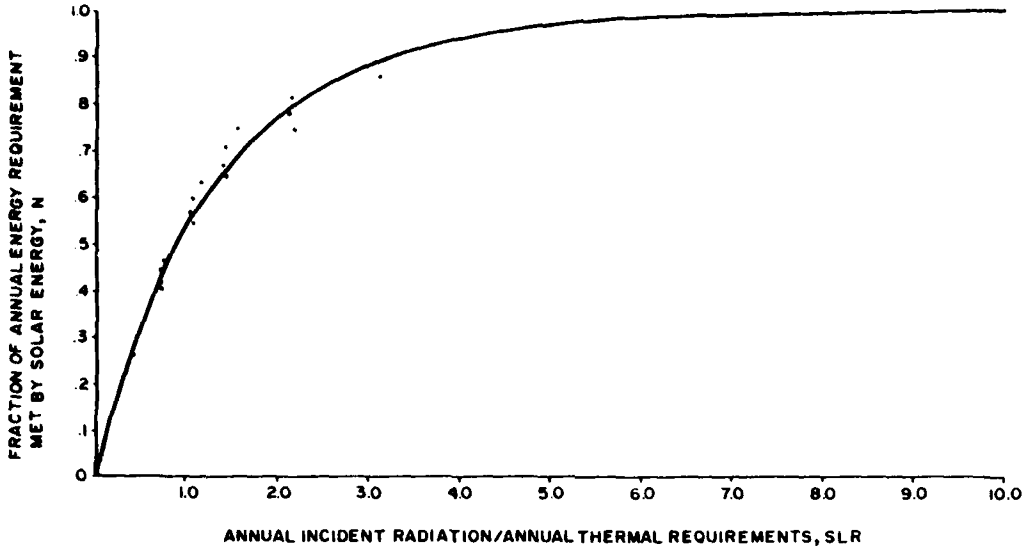

Figure 4. Universal curve for solar domestic hot water. (From D. C. Hittle, G. N. Walton, D. F. Holshouser, and D. J. Leverenz, *Predicting the Performance of Solar Energy Systems*, Technical Report E-98/ADA035608 [CERL, January 1977].)

Three such "universal curves" were produced: one for solar domestic water heating, one for solar space heating, and one for solar domestic water heating combined with space heating and cooling. Figure 4 presents the universal curve for solar domestic water heating.

The development of this approach was based on several assumptions. First, a singly glazed, flat-plate collector with a plate emissivity of .10 and absorptivity of .90 was taken as the reference collector. The collector's tilt from the horizontal depends on the solar heating application. For solar domestic hot water systems, the angle was assumed to be equal to the site latitude. All collectors were modeled as being unshaded and facing south. The heat exchanger effectiveness was fixed and the storage tank was assumed to contain approximately 2 gal of water/sq ft of collector area. The tank insulation had an overall thermal resistance of 19°F sq ft hr/Btu, and all system line losses were considered negligible.

Once the prospective building's thermal energy demands and the site solar insolation are known, the curve can be used to relate the system solar fraction to the total collector module area. To apply the curve for domestic water heating, an understanding of the following terms is required:

1. The annual solar radiation incident on the tilted collector array, Q_C, in Btu/sq ft/yr. Since long-term insolation data normally are referenced to a horizontal surface, these intensities must be corrected to account for the tilt angle of the collector array. The optimal tilt from the horizontal for solar domestic hot water systems is roughly equal to the latitude angle. In this case, Q_C may be computed using Equation 2,

$$Q_C = \frac{.99Q_H}{\cos(\Theta - 7)} \qquad \text{[Eq 2]}$$

where Q_H is the average annual insolation on a horizontal surface (in Btu/sq ft/year) and Θ is the site latitude angle in degrees. Long-term average daily values of Q_H have been tabulated for several National Weather Service Stations.[13]

2. The annual thermal energy requirement, Q_L. For the purpose of the universal curve this term is defined as the total annual thermal energy required for

[13] C. L. Knapp, T. L. Stoffel, and S. D. Whitaker, *Insolation Data Manual*, SERI/SP-755-789 (Solar Energy Research Institute, 1980).

domestic water heating. An expression for Q_L is given in Equation 1.

3. The solar load ratio, SLR. This quantity, defined as the ratio of annual radiation incident on the collector array to annual thermal energy requirements, is given in Equation 3:

$$SLR = \frac{Q_C A_C}{Q_L} \quad \text{[Eq 3]}$$

where A_C is the collector array area in sq ft. The SLR essentially measures the solar energy available to the system collector array relative to the total thermal load.

4. The percentage of thermal energy requirement provided by solar energy, η. This term, the fraction of Q_L provided by a collector array of area A_C, is related to SLR as given in Equation 4:

$$\eta = 1 - e^{-(.78(SLR)^{.93})} \quad \text{[Eq 4]}$$

Once the annual thermal load and the site insolation are known, the curve provides a quick and simple method for estimating the collector array area required to produce the solar fraction desired. An example application of this method is provided in Chapter 4.

The procedure for applying the modular design approach is as follows. The user estimates the annual hot water usage for the barrack under consideration and the annual solar radiation available at that site. The universal curve is applied to determine the collector array area required to produce the solar fraction desired. Table 5 is consulted for the appropriate system size for that collector area, and the detailed specifications developed for the components of that system are then used to procure it for the candidate building.

In adopting this approach, the quantity of user input needed has been kept to a minimum. As described, the only information necessary for the system design is an estimation of the barrack annual hot water usage and the site insolation.

3 SYSTEM DESIGN

Description

Based on the concept configuration (Figure 2) and the major component characteristics (Table 5), detailed designs were developed for the collector and HPS modules.

The collector module (Figure 5) consists of three interconnected collectors mounted in an adjustable aluminum frame. They have copper waterways and an aluminum enclosure, and are glazed with a single pane of glass. These materials were selected for their low maintenance and light weight. The collectors have internal headers to minimize the amount of external piping required. The aluminum framework was designed for both roof and ground mounting and to withstand high winds and substantial snow loads. The tilt of this framework from the horizontal can be adjusted onsite to allow its use at all continental United States latitudes.

A design feature of the modular collector concept is that of a "bank" of collectors, consisting of four interconnected collector modules (Figure 6). The first two modules of a bank are connected in parallel; the output of this assembly is series-connected to another group of two modules, also fixed in parallel. One bank is the minimum increment of area for the modular system.

There are several advantages to piping the collectors this way. First, flow balance within a bank is achieved because no more than six collectors are connected in parallel. (Equal flow among banks is achieved using calibrated flow restrictors at the outlet of each bank.) Second, the collector array is protected from damage caused by differential thermal expansion by the vertical pipe running between the two groups of six collectors within the bank. Third, vents allow air to be bled from the system high points. Finally, any bank may be isolated from the others by isolation valves at the bank inlet and outlet.

Using propylene glycol as the heat transfer fluid provides simple, reliable freeze protection for the solar collector loop.

The HPS module (Figure 7) contains the following components:

Circulation pump

Expansion tank with sight glass

Air separator

Fill-drain port

Temperature and pressure gauges

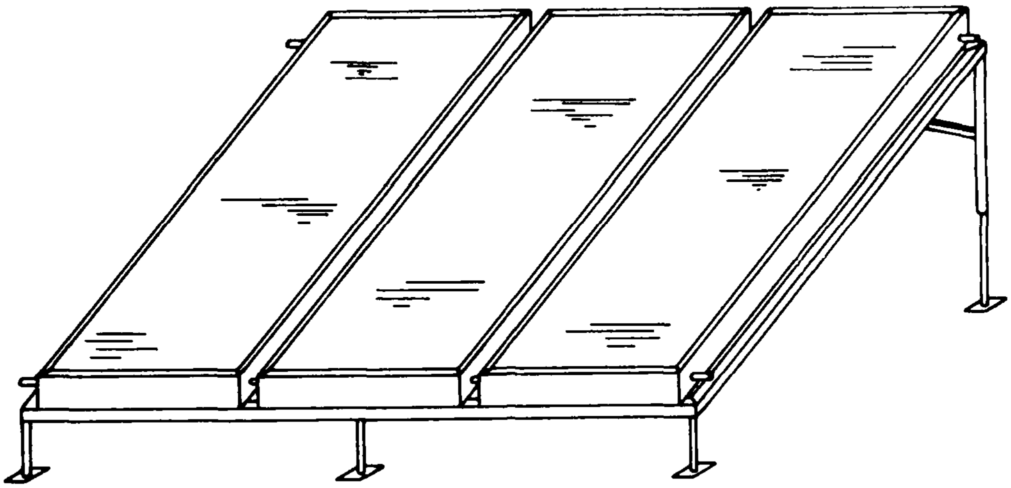

Figure 5. Collector module.

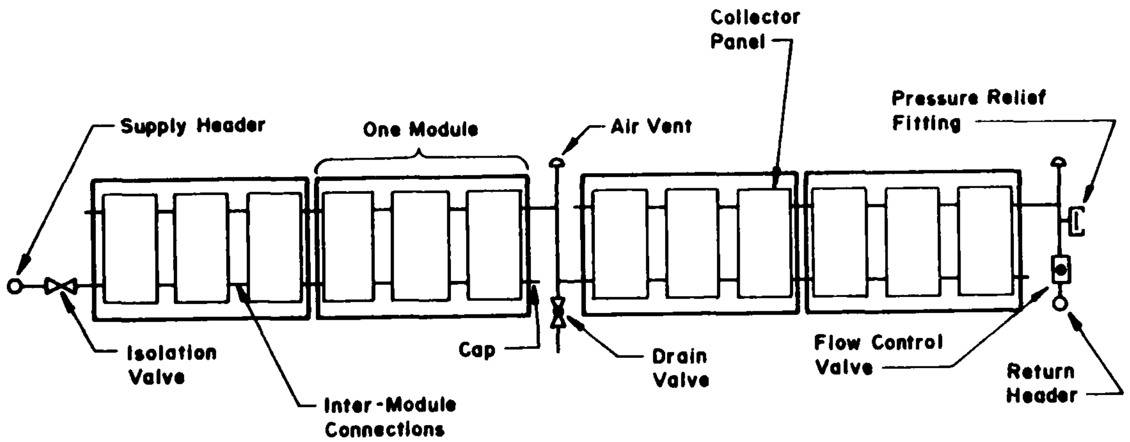

Figure 6. Collector bank piping.

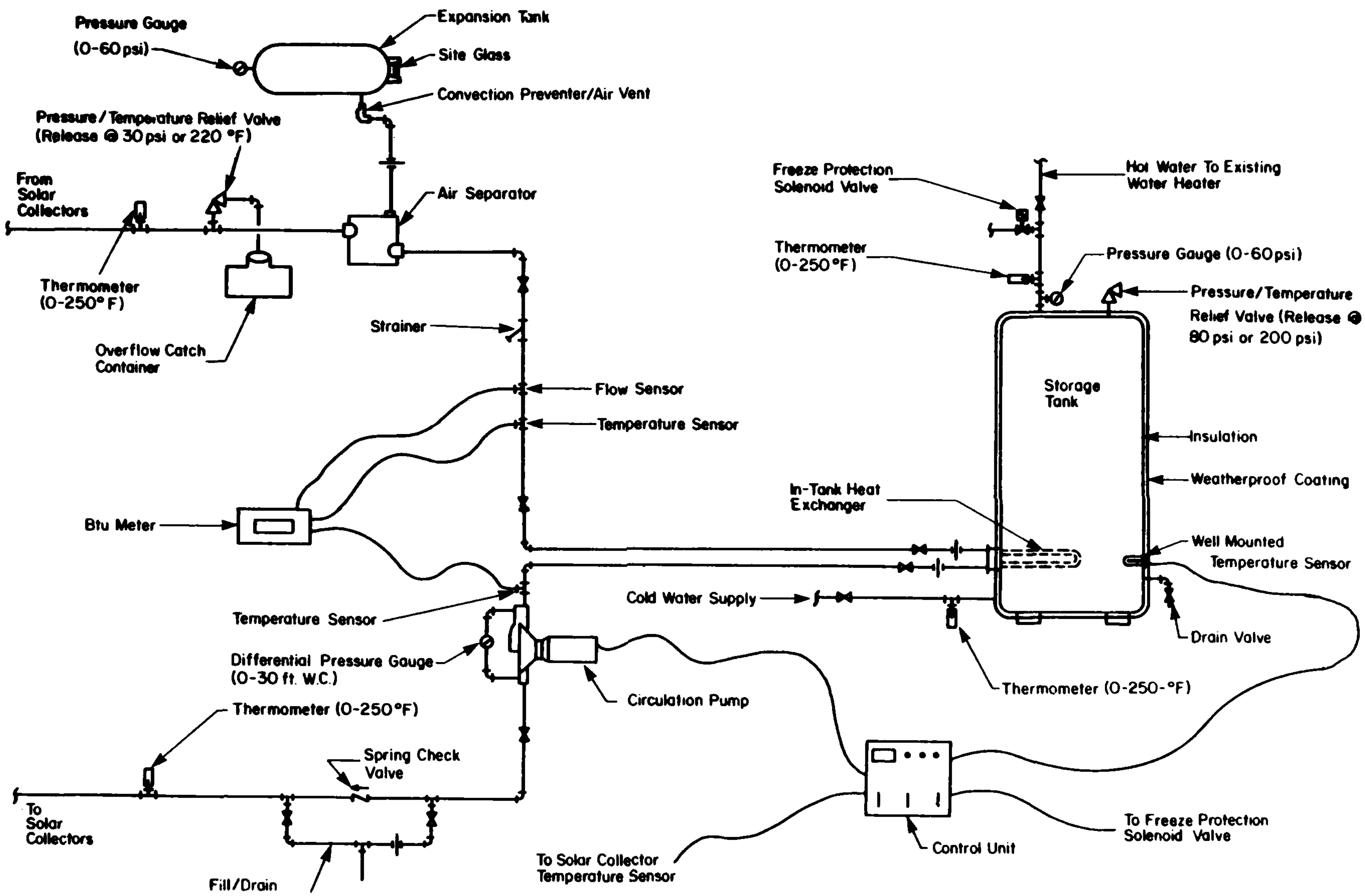

Figure 7. HPS module piping diagram.

Pressure relief valves

Check valve

Electronic differential temperature controller

Btu meter

Elapsed time meter

Insulated tank surrounded by a weather jacket

In-tank U-tube heat exchanger

Tank freeze protection assembly.

These components are manufactured as two assemblies: (1) a water storage tank with a built-in heat exchanger and related accessories, and (2) the pump, controller, and other components housed in a metal cabinet.

The circulating pump has a low-head design and was sized to provide a design flow rate of 6 gpm per bank of modules at a head equal to the pipe friction loss in a typical installation. The pump does not develop enough head to fill the system with heat transfer fluid when the solar collectors are mounted on the roof. Therefore, roof-mounted collectors require a separate fill pump; the heat transfer is introduced into the system at the fill-port connection.

Thermal expansion of the fluid in the collector-heat-exchanger piping circuit is accommodated in three ways. First, the expansion tank is sized to contain any increase in fluid volume experienced during normal operation. If the expansion tank fills with fluid during some unusual condition, such as overheating as might occur in a power outage, fluid is released into a catch-basin through a low-pressure (30 psig) relief valve. High-pressure relief valves (124 psig) located on the collector module banks provide the third level of defense against potential damage by excessive system pressures.

Pressure and temperature gauges in the pump-controller assembly permit easy monitoring of the pump head and temperature change across the collector array. This information is useful for estimating system performance and for diagnosing malfunctions. The elapsed-time meter (connected to the circulation pump) is also used to test for proper system operation.

A differential temperature controller operates the circulating pump. When the difference between the temperature of the collector fin and that of the water in the storage tank exceeds a preset value (usually about 15°F), the pump is turned on. It remains on until the temperature difference drops to less than a second preset value (about 5°F). The pump controller also contains a second pair of relay contacts operated by comparing the input from the storage temperature sensor to a preset temperature. This temperature set-point is used to activate the freeze protection system for the hot water storage tank. A spring check valve in the piping circuit prevents thermosiphoning in the collector-heat-exchanger loop when the pump is off.

A Btu meter in the collector-heat-exchanger circuit calculates and records the amount of energy transferred from the solar collector array into the hot water storage tank.

The water heating assembly is composed of a large metal tank with a built-in heat exchanger. The heat exchanger, assembled from copper tubes shaped in the form of a "U" bundle, is located near the bottom of the tank. Cold water enters the tank at the bottom and is heated by natural convection as hot heat-transfer fluid circulates through the heat exchanger. The hot water rises to the top of the tank and from there goes to the existing water heater. The water heating tank assembly is insulated to reduce heat loss and the insulation is surrounded by a weatherproof jacket.

It is possible that prolonged periods of cold, overcast weather combined with a low demand for hot water may cause the storage tank water to freeze. (Because of its large size, the storage tank will usually have to be located outdoors in retrofit installations.) To preclude freeze damage, the tank has been fitted with a simple, but effective, freeze protection system. When the temperature of water in the tank drops below a preset value (about 35°F), the temperature controller actuates a normally closed solenoid valve in a small pipe leading from the top of the tank to a drain. This action permits a steady inflow of relatively warm make-up water that raises the water temperature in the tank to prevent freezing. Overtemperature protection is provided by the temperature-pressure relief valve.

Summary of Features

The collector module consists of a three-collector assembly, piped in banks and mounted on a tiltable aluminum rack for ground or roof placement. The HPS module contains the system pump, expansion tank,

controller, heat exchanger, tank, Btu-meter, check valve, pressure relief valve, air separator, pressure gauges, and thermometers. Features of the installed system include provisions for filling and draining the collector array, inherent flow balance among collectors, freeze protection of the collector loop, over- and under-temperature protection of the tank, and an allowance for differential thermal expansion in the collector array. The size of the system to be installed is readily determined by a simple, manual calculation requiring minimal user input. Lessons learned from the installations of a prototype modular system are discussed in Chapter 4.

4 TEST AND EVALUATION

System Sizing

Building 1182, a barrack at the Naval Construction Battalion Center (NCBC), in Port Hueneme, California, was selected as the site to test the concepts described in the two preceding chapters. The system sizing procedure developed in Chapter 2 was applied to the Port Hueneme barrack. Barrack records indicated that the average occupancy was 80 persons. Assuming an average daily hot water consumption of 30 gal/person/day and a temperature rise of 55°F, Equation 1 can be used to compute the annual thermal energy requirement for domestic water heating:

$$Q_L = \rho V C_p \Delta T$$

$$= (8.3\ \text{lb/gal})(80\ \text{persons})$$

$$\times \left(30 \frac{\text{gal}}{\text{person day}}\right)\left(365 \frac{\text{day}}{\text{year}}\right)$$

$$\times \left(1 \frac{\text{Btu}}{\text{lb}^\circ\text{F}}\right)(55^\circ\text{F})$$

$$= 4.0 \times 10^8\ \text{Btu/year}$$

Equation 2 gives the approximate annual radiation per sq ft of collectors. Taking a value of 1550 Btu/sq ft/day for Q_H from C. L. Knapp et al. and using 35° for the site latitude, Q_C can be computed.

$$Q_C = \frac{(.99)(1550\ \text{Btu/sq ft/day})(365\ \text{day/year})}{\cos(35^\circ - 7^\circ)}$$

$$= 6.3 \times 10^5\ \text{Btu/sq ft/year}$$

Since each collector has an area of approximately 20 sq ft and there are 12 collectors (4 modules) per bank of collectors, the effective collector area per bank is 240 sq ft. Therefore, the annual radiation incident on a bank is 1.5×10^8 Btu/year.

For this installation, it was decided to design for a 70 percent annual solar fraction. The universal curve for solar domestic water heating (Figure 4) indicates that, for a solar fraction of 70 percent, a value of 1.5 should be used for SLR. In this case, Equation 3 can be written as:

$$1.5 = \frac{(6.3 \times 10^5\ \text{Btu/sq ft/year})(240\ \text{sq ft/bank})}{(4.0 \times 10^7\ \text{Btu/year})} N$$

where N is the number of banks required. Solving for N indicates that four banks of collectors (or 16 collector modules) are required. Table 5 shows that a collector system consisting of 48 collectors is a System I.

Procurement and Installation

From the generalized module schematics (Figures 5 and 7) and the appropriate component sizes listed in Table 5, detailed specifications were developed for the collector module and a System I heat exchanger-pump-storage tank module.

As usual, the contract for the HPS module was awarded to the low bidder; however, with permission of the Naval contracting authorities, a method different from low bid was used to contract for the solar collector modules. That contract was awarded based on which unit collected the most energy per dollar of cost. Bidders were required to submit, along with their price for a specific number of collector modules, certified test data (ASHRAE 93-77 method) describing the efficiency of their collector with additional data on flow rate, pressure head loss, and volume of fluid in each collector.[14] These data were used as input to a computer program that calculated the amount of solar energy collection expected at the Port Hueneme site over a period of 1 year. Site-specific temperature, solar insolation, and hot water load data were used for these simulations. Bid prices ranged from $24,800 to $58,800. The calculated performance/cost ratios were normalized, then weighted to reflect the importance of this criterion in selecting the contractor.

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[14] American Society of Heating, Refrigerating, and Air-Conditioning Engineers, *Methods of Testing to Determine the Thermal Performance of Solar Collectors*, ASHRAE Standard 93-77 (ASHRAE, 1978).

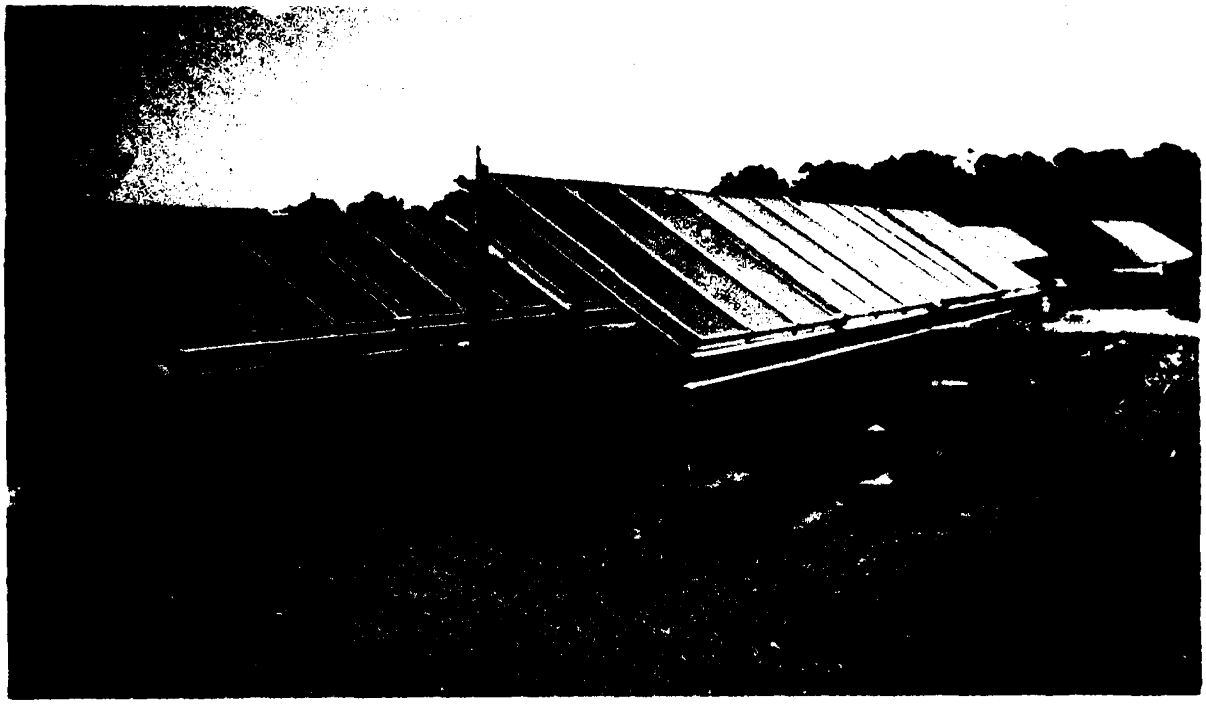

Figure 8. Modular system collector array.

While the solar collector and HPS modules were being fabricated, drawings were prepared that described in detail the installation of the modules, piping, and ancillary components at Building 1182. A contract Statement of Work for installing the solar heating system was also prepared. After delivery of the modules, an installation contract was awarded by the Public Works Department, NCBC, Port Hueneme. Figures 8 through 10 are photographs showing the installed system. Table 6 summarizes the system installed costs.

Thermal Performance

Tests were conducted to determine the thermodynamic performance of the prototype modular solar water heating system. Although detailed testing was not feasible because of the system's limited amount of instrumentation, reasonable estimates of its overall thermal performance could be obtained. The insolation during the tests was measured with a Licor Model 1776 integrating pyranometer, and the system thermal output was determined from readings of an ISTA W3 Btu meter.

Test results are summarized in Table 7. For the dates shown, the total solar energy incident on the collector array (E_{in}) and the system thermal output (E_{out}) are tabulated. The duration of the test and the average tank temperature during the measurement period (T_{tank}) are listed as well. As expected, the system daily efficiency (computed by dividing E_{out} by E_{in}) is dependent on the average tank temperature. From these results, the system's normal operation may be understood. The barrack occupants typically consume little

Table 6
System Costs

18 Collector Modules (16 installed, 2 spare)	$24,800
Heat exchanger-pump tank-module	18,500
Preparation of installation drawings	14,500
Installation	24,900
Total	$82,700
Installed gross collector area	883 sq ft
Cost per unit of area	$94/sq ft

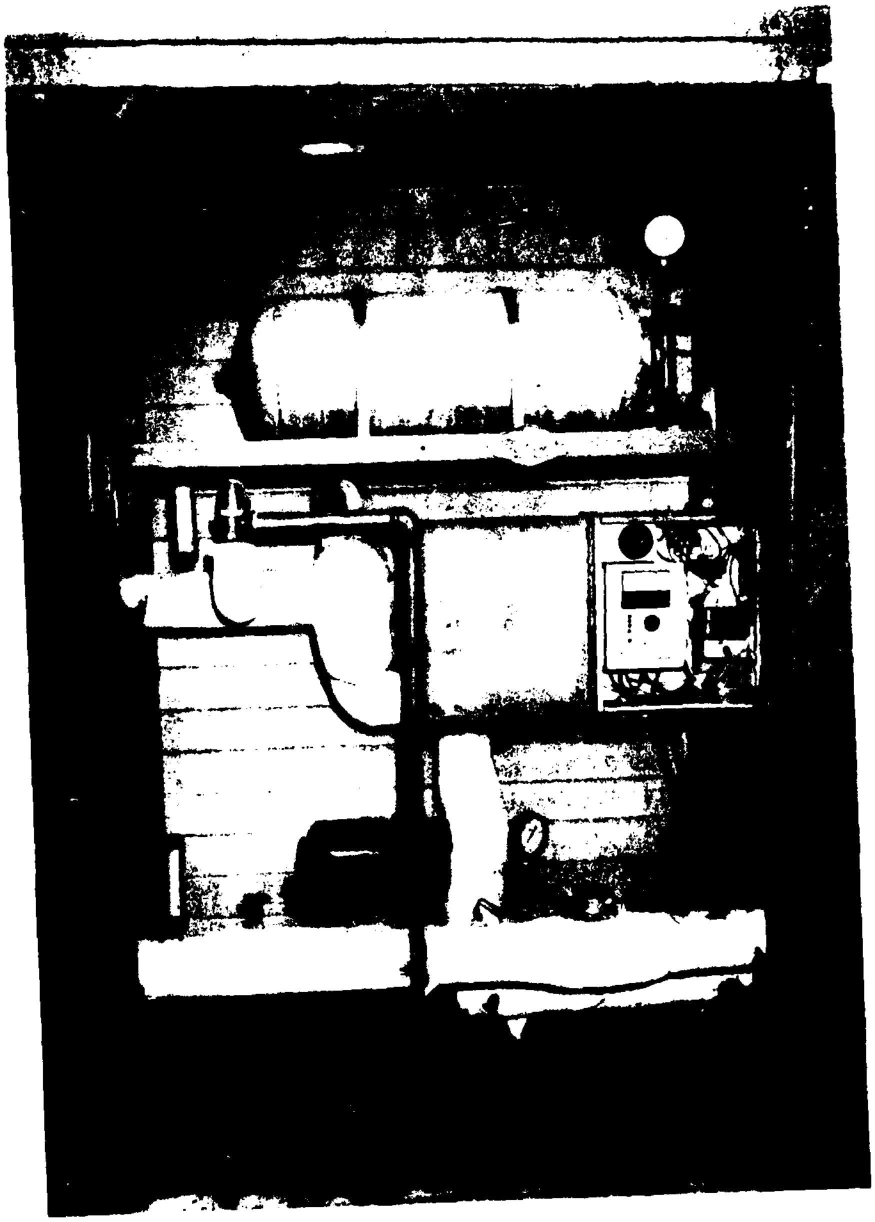

Figure 10. Modular system pump-controls package.

Table 7
Thermal Performance of the Prototype System

Date	E_{in} (Btu × 10^5)	E_{out} (Btu × 10^5)	Duration (Hrs)	T_{tank} (°F)
28 Mar 83	8.6	4.4	5	80
29 Mar 83	17.3	7.2	7	95
30 Mar 83	16.5	4.4	6	120
31 Mar 83	18.1	7.8	7.5	90

hot water during the daylight hours. Thus, on a sunny day with no hot water usage, the 1200-gal storage tank would be heated from about 65°F in the morning to roughly 125°F by the time the system shuts off. This corresponds to an energy delivery rate of approximately 100,000 Btu/hour. In the late afternoon and evening hours, the occupants use all of the solar-heated water -by morning reducing the temperature of water in the tank to that of the incoming makeup water. Under these conditions, the system can be expected to deliver between 700,000 and 800,000 Btu per day.

Concept Evaluation

At the onset of this project, the primary benefits of a modular approach to solar design were seen as two-fold: (1) a potential reduction in solar system design and installation costs, and (2) the elimination of common design errors. In this section, the success of the project in achieving these goals is examined.

The total price of the prototype system for Building 1182 was $94/sq ft of collector, including fabrication and installation of all components, and the preparation of detailed installation drawings. An analysis of *DOD Solar Energy Project Summaries*[15] indicated that the costs of previous solar DHW systems used at Army facilities have ranged from $33 to $169/sq ft.

The extent to which solar energy systems are incorporated at military facilities in the future will ultimately be determined by cost. During the time that the prototype system was being installed, the U.S. Army Construction Engineering Research Laboratory (CERL) developed (as part of a separate research effort) an automated procedure for estimating the economic feasibility of four distinct solar thermal applications. Known as SOLFEAS,[16] the method allows the user to project payback times for solar domestic hot water systems.

Several SOLFEAS runs were then performed to determine under what conditions the prototype system would be economically justifiable. The results can be summarized as follows: for a system costing $94/sq ft of collector, energy prices must increase to $15/MBtu before that system would recover its initial cost within a 25-year period. Given that the system at Building 1182 is competing against natural gas costing $4.50/MBtu, it is clear that the NCBC installation will not be cost-effective until fuel prices rise substantially. In fact, the solar DHW system at this site could pay for itself in 25 years only if its installed cost were in the neighborhood of $25/sq ft of collector area. Even if the prototype system were competing against distillate fuel costing $8.50/MBtu, SOLFEAS indicates that the installed solar system costs must be decreased by $34/sq ft before the system would pay back in the required time.

It was felt that modularization had potential for reducing solar system costs in two ways. First, most of the system components are factory fabricated, presumably costing less than onsite assembly. Second, several identical systems could be purchased at the same time so that an economy of scale could benefit the solar program.

It is difficult to draw firm conclusions from the installation of a single prototype system. However, given current market conditions, it is unlikely that even wide-scale implementation of modular solar DHW systems by DOD would result in the required savings of $34/sq ft of collector area.

As fuel prices increase, the economics of solar energy will improve and wide-scale adoption of solar DHW systems by DOD may be warranted. In the interim, the lessons learned from installing the prototype system can still be applied to meet the second

[15] U.S. Department of Defense, March 1980.

[16] D. M. Joncich and C. W. Sohn, *SOLFEAS: An Interactive Program for Estimating the Economic Feasibility of an Active Solar Thermal Energy System*, Technical Report E-180 ADA-125682 (CERL, 1983).

objective of the project the elimination of common design errors.

Although long-term thermal performance and reliability of the prototype system have not yet been established, the results to date indicate that the overall system design is sound. The system of Building 1182 is operating properly and has demonstrated an ability to deliver between 0.5 and 1 MBtu of energy per day for domestic water heating. The system sizing procedure, based on the universal curve, appears reasonably accurate as well; an extrapolation of the quantity of energy the system delivers during the sunny spring days of testing would correspond roughly to 60 to 70 percent of the annual thermal load projected. The design concepts of the modular approach can be transmitted to the field today via recommended revisions to existing military solar design guidance.

This information transfer will proceed as follows: the system shown schematically in Figure 2 will be proposed as a "standard" system for solar domestic water heating. The detailed drawings and specifications developed in the course of the project will be revised and incorporated into the appropriate Army documents.[17] Although subsequent revisions to these documents are likely, the ultimate goal is to ensure that solar systems at DOD facilities in the future will be as cost-effective and reliable as possible.

5 CONCLUSIONS

This report described the design and installation of a modular solar domestic water heating system. Based on an evaluation of the system concept and hardware, it is concluded that:

1. The installed modular system, while not economically feasible under current market conditions, may be cost-effective in the future if fuel prices increase substantially.

2. The prototype system's thermal performance is near its design goal; the system configuration can be adopted by the Department of Defense as a "standard" for future solar DHW applications.

[17] U.S. Department of the Army, *Solar Energy Systems*, Technical Manual (TM) 5-804-2 (HQDA, August 1982); U.S. Department of the Army, *Military Construction, Solar Equipment*, Corps of Engineers Guide Specification (CEGS) 13985 (May 1982).

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Metric Conversion Chart

1 Btu = 1055 joules

1 sq ft = 0.0929 m^2

1 gal = .0038 m^3

1 hp = 745.7 W

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